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DROP TEST RESULTS FOR THE COMBUSTION ENGINEERING MODEL NO. ABB-2901 FUEL PELLET SHIPPING PACKAGE

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ABSTRACT

The U.S. Nuclear Regulatory Commission (USNRC) contracted with the Packaging Review Group (PRG) at Lawrence Livermore National Laboratory (LLNL) to conduct a single, 30-ft shallow-angle drop test on the Combustion Engineering ABB-2901 drum-type shipping package. The purpose of the test was to determine if bolted-ring drum closures could fail during shallow-angle drops.

The PRG at LLNL planned the test, and Defense Technologies Engineering Division (DTED) personnel from LLNL's Site-300 Test Group executed the plan. The test was conducted in November 2001 using the drop-tower facility at LLNL's Site 300. Two representatives from Westinghouse Electric Company in Columbia, South Carolina (WEC-SC); two USNRC staff members; and three PRG members from LLNL witnessed the preliminary test runs and the final test.

The single test clearly demonstrated the vulnerability of the bolted-ring drum closure to shallow-angle drops—the test package's drum closure was easily and totally separated from the drum package.

The results of the preliminary test runs and the 30-ft shallow-angle drop test offer valuable qualitative understandings of the shallow-angle impact.

- A drum package with a bolted-ring closure may be vulnerable to closure failure by the shallow-angle drop, even if results of the steep-angle drop demonstrate that the package is resistant to similar damage.
- Although there exist other mechanisms, the shallow-angle drop produces closure failure mainly by buckling the drum lid and separating the drum lid and body, which the bolted ring cannot prevent.
- Since the closure failure by the shallow-angle drop is generated mainly by structural instabilities of a highly discontinuous joint, the phenomenon can be rather unpredictable. Thus, a larger-than-normal margin of safety is recommended for the design of such packages.
- The structural integrity of the bolted-ring drum closure design depends on a number of factors. To ensure that the drum closure survives the shallow-angle drop, the following general qualitative rules should be observed:
  - The drum closure components should be quality products made of ductile materials, and the torque value for tightening the bolted ring should be included in the SAR and operating procedures to ensure quality.
  - The package should not be too heavy.
  - The package internal structure should be impact-absorbent and resistant to disintegration and collapse under high compressive load. However, a strong internal structure may defeat the purpose of protecting the containment vessel from damage during a free drop.
- If not previously tested, drum packages with bolted-ring drum closures should be drop-tested at shallow angles. Due to the unpredictable nature of the behavior, the demonstration should be completed by test and on a case-by-case basis. The test plan should take into account the behavior's sensitivity to the details of the package design and the impact condition.

- Because the shallow-angle drop can open the drum closure, organizations using these types of drum packages should assess the consequences of exposing the radioactive contents in the containment vessel to unconsidered external elements or conditions.

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1.0 INTRODUCTION

Steel cylindrical drums have been used for many years to transport radioactive materials. The radioactive material inserted into the drum cavity for shipping is usually restrained within its own container or containment vessel. For additional protection, the container is surrounded or supported by components made of impact-absorbent and/or thermal-insulation materials. The components are expected to protect the container and its radioactive contents under severe transportation conditions like free drops and fires.

Due to its simplicity and convenience, bolted-ring drum closures are commonly used to close many drum packages. Because the structural integrity of the drum and drum closure often play a significant role in determining the package's ability to maintain sub-criticality, shielding, and containment of the radioactive contents, regulations require that the complete drum package be tested for safety performance.

The structural integrity of the drum body is relatively simple to understand and analyze, whereas analyzing the integrity of the drum closure is not so simple.

Steep-angle drop tests

The common bolted-ring drum closure has been tested and shown to be resistant to damage under the regulatory 30-ft *free-drop* condition. Frequently, only steep-angle drop tests are used to test drum packages because they are generally recognized to produce the largest impact forces. In most steep-angle drop tests, a drum package is dropped upside down (the open end of the drum) at a "steep angle," that is, with the drum axis so oriented that the center of gravity of the package is aligned vertically with the center of the impact area. The so-called "end-on," "top-down," and "center-of-gravity (c.g.)-over-corner" drops are examples of steep-angle drops.

Under loads, the integrity of the drum closure depends not only on the magnitude of the applied load but also on the *direction* of the load relative to the closure geometry. Indeed, the steep-angle drop can produce large deformations due to its greater force, but it tends to crush the drum closure components (the drum body, lid, and ring) together due to its impact direction. Thus, the drum closure seldom opens during steep-angle drops.

Shallow-angle drop tests

On the contrary, openings have occurred in shallow-angle drop tests. In the shallow-angle drop, the drum package is dropped upside down with its axis nearly parallel to the horizontal plane. The impact force of the shallow-angle drop is considerably smaller than that of the steep-angle drop, but its line of action lies almost in the plane of the drum lid. Thus, the impact force can easily cause the lid to buckle outward and move away from the drum body. While the shallow-angle drop does not have the great force of the steep-angle drop, it has the unique ability to drive the drum closure components apart.

The shallow-angle drop is frequently ignored in test plans for the bolted-ring drum package simply because the shallow-angle drop is not known to produce great impact forces.

Failures leading to the LLNL test

Few people are aware of the studies by Lewallen [1] and Towell [2] that recommended weight limits for preventing closure failures. In addition, several shallow-angle drop tests conducted by the Department of Energy at the Savannah River Site in Aiken, South Carolina [3], have demonstrated the complete opening of the drum closure. The most recent drum closure failure, a 9975 package during a 30-ft, 17.5º shallow-angle drop in March 2000 [4], prompted Westinghouse Savannah River Corporation (WSRC) to replace the package's bolted-ring drum closure with a bolted-lid system.

The failure was brought to the attention of the U.S. Nuclear Regulatory Commission who contracted the Packaging Review Group at Lawrence Livermore National Laboratory to conduct a single, 30-ft shallow-angle drop test of a drum package. The purpose of the test was to determine if a bolted-ring closure could fail during a shallow-angle drop.

The LLNL shallow-angle test

The PRG at LLNL planned the test and DTED personnel from LLNL's Site-300 Test Group executed the plan. WEC-SC generously donated the empty test drum package. The test was conducted in November 2001 using the drop-tower facility at LLNL's Site 300.

This paper documents the procedures and results of the preliminary test runs and the final shallow-angle drop test. Section 2.0 describes the design and preparation details of the test drum package. Section 3.0 outlines the test setup and preliminary-test-run results. Section 4.0 reviews the 30-ft, 17.5º shallow-angle drop test and damage to the test package. Section 5.0 summarizes the findings of this test program. In addition to the examination of the final damage to the package components, the analysis of the high-speed digital video record of the 30-ft drop test provided significant understanding of the package behavior and damage mechanism in the shallow-angle drop. Both the observation of the final damage and the analysis of the video record contributed to the conclusions given in Section 5.0. Unfortunately, the limited space of this paper does not allow inclusion of the video record analysis. Interested readers are referred to the original test report for details [5].

2.0 TEST PACKAGE PREPARATION

The empty drum package supplied by WEC-SC is the Combustion Engineering Fuel Pellet Shipping Package, Model No. ABB-2901. The Safety Analysis Report (SAR) [6] describes its design and safety performance. Figure 1 shows an engineering drawing from the SAR.

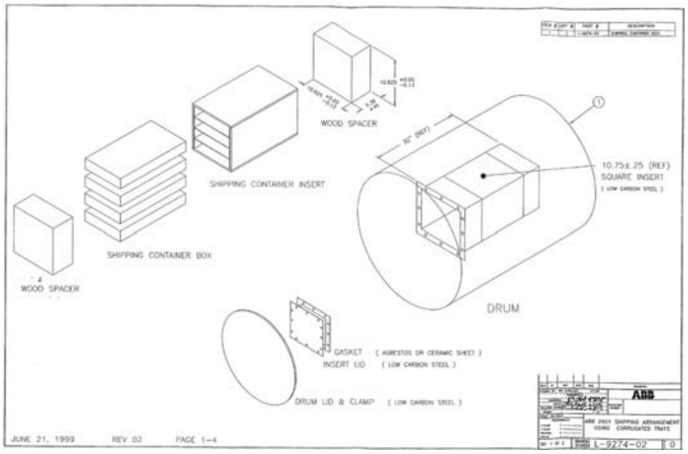

Figure 1. ABB Drawing ABB-L-9274-02-01

The cylindrical drum package, measured about two feet in diameter and three feet in height is a typical 55-gallon drum package. The open end of the thin-walled steel drum is closed using a flat circular steel lid and a bolted steel ring with a C-shaped cross-section. The bolted-ring closure device is common to many drum packages. To close the drum, the closure ring wraps around the drum opening and grips the rims of the opening and the lid with its C-shaped cross-section. The ring is closed using a bolt, which passes through two lugs or nuts welded to the two ends of the open ring. The gripping pressure is adjusted by tightening or loosening the closure bolt.

Inside the drum cavity is a deep square steel box, used to contain the fuel pellets for shipment. The inner compartment (i.e., “containment box”), approximately 10" × 10" × 30" in size, is supported in the radial direction of the drum using hardboard and plywood rings that have a square hole at the center. The box is also supported in the axial direction using round solid plywood boards (without a hole). The open end of the box is closed with a square steel lid bolted to the box-opening flange using twelve, 1/2 × 13 UNC nuts threaded onto their corresponding studs, mounted on the flange. During shipment, fuel pellets are stored on corrugated trays inside four shallow rectangular storage boxes. The storage boxes are then inserted into the shipping container insert inside of the containment box. The storage boxes and insert are prevented from axial movements by two wood spacers located at the two ends of the containment box. The containment box with its contents is prevented from sliding out of the drum by the front hardboard ring and a small steel internal tab tack-welded to the inner drum wall. Empty drum-cavity space between the hardboard ring is filled with low-density thermal-insulation materials. The drum cavity top and bottom are covered with thermal-insulation sheets taped to one of the round solid plywood boards.

Preparing the Package at the Livermore Site

WEC-SC shipped the empty drum package, in its normal tied-down position, to LLNL’s Site 300. Three LLNL staff members inspected the package in October 2001 and found its visible parts generally matching the descriptions in the Combustion Engineering drawings. The containment box was not removed for inspection due to blockage by the metal internal tab. However, the metal internal tab tack-welded to the inner drum wall (whose function is to stop the containment box from sliding), appeared rather feeble considering the weight of the containment box and contents.

In November 2001, a team of technicians from LLNL’s Site-300 Test Group prepared the empty drum package for testing. The two WEC-SC representatives and two LLNL PRG staff members were present to witness the operations. The empty test drum weighed 471 pounds before the LLNL team inserted a predetermined amount of prefabricated steel plates into the four storage boxes in the test package to simulate the mass of fuel pellets. Closure of the inner compartment was provided by tightening the twelve 1/2 ×13 UNC containment-box lid nuts to 30 ft-lb.

The fully loaded test package weighed 655 pounds, which is just below the licensed maximum total weight of the package of 660 pounds. When closing the drum after loading, a defect in the threads of the closure bolt stripped the threads in the tightening lug of the drum-closure ring, such that it could not hold the specified tightening torque of 75 ft-lbs. Thus the actual final weighing of the test package was not performed until shortly before the 30-ft drop test on November 15, when the LLNL team closed the drum with a replacement ring specially delivered from WEC-SC (see Fig. 2).

Note: The WEC-SC representatives specified the value of 30 ft-lbs for the closure nuts of the containment-box lid and the value of 75 ft-lbs for the drum closure ring bolt, since neither was specified in the SAR.

Figure 2. Packaging Closure, Bldg. 858

3.0 TEST SETUP AND PRELIMINARY TEST RUNS

The Drop Tower Facility at LLNL’s Site-300 (see Fig. 3), was used to perform the 30-ft drop test. The Facility was initially designed for drop testing heavy weapons-related packagings weighing up to 6,000 lbs, and is used to perform both guided and unguided (free) drops from heights up to 100 ft. The Facility has a ten-foot square unyielding surface built, from top to bottom, with (1) a top steel plate 3- 9/16" thick over (2) a 1" grout layer over (3) a 2 ft-thick reinforced concrete pad over (4) a square, concrete tank back-filled with gravel approximately 5 ft deep. The Facility is more than adequate for the 30-ft drop test.

To ensure a free drop, the steel ropes used for guided drops were removed and pulled back prior to the setup for the 30-ft drop test. A single sling was used to suspend the package so that the effect of the release operation on the drop orientation could be minimized. For the 30-ft, 17.5º shallow-angle drop, the package was positioned and suspended according to the Test Plan. The position of the closure-ring lug for the test was changed from the original plan. The original plan called for the lug to be located 90 degrees, as opposed to the current 180 degrees, from the impact point. The 30-ft drop height was determined using a pre-measured plumb line. A pneumatic device released the suspension sling with the package. An attached long rope stopped the falling suspension sling before it caught up with the impacting package.

Figure 3. Site 300 Drop Test Tower

Two high-speed (500 frames per second) digital video cameras were setup to record the motion of the impacting package. One camera was set to record the side view, and the other to record the top (lid) view of the impacting package. Two grid boards were erected around the intended impact area on the opposite side of the cameras to provide a plain background for the video photography. The boards had six-inch-wide and six-inch-apart black horizontal lines to provide a length scale for the video records.

For the puncture test, the LLNL test team fabricated a puncture bar according to the standards set forth in 10 CFR Part 71 [7]. The bar was about 40" long, and was joined to its own base plate with four welded triangular gussets. (Although the intent was to bolt the puncture bar base plate to the unyielding target surface for the puncture test, the puncture bar test was deemed to be unnecessary after the initial failure of the package.)

On the morning of November 14, the LLNL test team conducted two preliminary test runs of the 30-ft shallow-angle drop using two common 55-gallon drums as the test package. One drum was filled with water; the other with solid ice. The solid-ice test-drum package was produced by placing a 55-gallon drum of water overnight in an environmental test chamber. A thermocouple placed at the center of the drum cavity confirmed the formation of solid ice. As generally expected, the water-filled drum failed miserably. Figure 4 shows the severely deformed drum components. The high hydrodynamic pressure generated by the impact apparently caused the large deformations. Being pushed outward, the drum body and lid deformed in the horizontal directions, which offered the least resistance.

Figure 4. Damage to Lid, Closure Ring and Drum Along Side of Damage to Previously Dropped 35-Gallon, Water-Filled Drum

At first glance, the solid-ice drum did not appear to fare much better than the water-filled drum. Closer examination, however, revealed that the ice in the solid-ice drum was not a true solid, i.e., there were numerous radial fracture surfaces in the ice from the outside of the drum to the inside, and there was a basketball- to beach-ball-sized volume of liquid water inside the ice, near the bottom of the drum. Without analyzing the results of this preliminary test run in detail, it appeared that the ice behaved more like liquid water than expected because the drum and its closure did not maintain its integrity under the high-impact forces.

The results of the preliminary test runs clearly demonstrated that the integrity of a drum closure depends heavily on the structural integrity of the internal components of the drum.

4.0 30-FT FREE-DROP TEST AND RESULTING DAMAGES

The 30-ft free drop of the test package was conducted on the morning of November 15, 2001. The weather conditions were nearly perfect: winds light and variable, light overcast, and temperatures around 70°F.

After the test team fitted the test drum with the replacement closure ring from WEC-SC, the ring-closure bolt was tightened to the recommended torque value of 75 ft-lb, which the WEC-SC had specified on November 13th. The test package was then properly positioned, suspended, and lifted to a height of 30 feet from the surface of the unyielding target. The package was dropped, and the test was completed, without any apparent difficulties with the operating procedures or the test hardware. The drum, however, failed with the lid enclosure ring completely separated from the drum.

Figure 5 shows the final position of all drum components after the drop.

The following subsections include a description of each component and an analysis of the damage sustained during the shallow-angle drop test.

Figure 5. Post-test Component Orientation

4.1 Drum lid and closure ring

The lid and ring flew off together during the test and remained together after the test. They showed minimal out-of-plane deformation, i.e., they remained a planar structure. This indicates that the large buckling deformation of the lid-and-ring assembly that led to the separation of the assembly from the drum body was basically elastic. The assembly showed only large in-plane permanent deformation in the impact area. The impact produced an approximately 12-in.-long straight edge of the lid-and-ring assembly. The lid adjusted itself to this large in-plane deformation with minor out-of-plane local buckling, while the ring accommodated the large deformation by in-plane bending.

4.2 Plywood boards between the lid and containment box

The two round solid plywood boards (one covered with a thermal insulation sheet), which occupied the space between the drum lid and the fuel-pellet containment box, suffered much less damage than their neighbors. This fact suggests that the boards had not borne or transmitted significant loads. Thus, their ejection from the impacting package consumed very little of the impact energy. Consequently, they were not able to contribute much to the ejection of the lid-and-ring assembly. Figures 6 and 7 show the damage suffered by the drum lid and upper drum body.

Figure 6. Drum Lid Close-up (Top-down)

Figure 7. Post-Test Upper Drum-Body Close-Up

4.3 Hardboards and plywood rings at the impact end

Except for the plywood ring at the front, the hardboard and plywood rings around the impact end of the fuel-pellet containment box were fractured and crushed in the bottom area underneath the box. The severity of the damage suggests that the bottoms of the rings were in the major load path of the impact. The collapse of the rings allowed the impact to easily produce a large buckling deformation in the drum-lid-and-closure ring assembly. Had the rings been stronger, or had the test package been positioned to hit the ground at a corner of the containment box, the ejection of the lid-and-ring assembly might not have occurred so easily.

4.4 Fuel-pellet containment box

The fuel-pellet containment box had only minor damage at the impact end. The presence of the solid square wood block inside the box opening at the impact end might have helped limit the extent of the damage. A technician noticed that some of the closure bolts in the box-opening flange were slightly displaced off the centerline of their base holes. A slight deflection of the impacting side of the box was visible. The deflection could be easily felt by touch.

4.5 Drum body

Similar to the lid-and-ring assembly, the round drum opening was flattened in the impact area. In addition, the round opening appeared slightly oval in the horizontal direction. This deformation was probably due to the compressive action of the vertical impact force rather than the bursting action of disintegrated contents, as in the case of the water-filled drum in the preliminary test runs.

The slight local buckling deformation of the drum opening near the impact area indicated the high intensity of the compressive action (see Fig. 8).

4.6 Other components

The internal tab tack-welded to the inner drum body to prevent the containment box from sliding out of the drum cavity became ineffective due to the destruction of the hardboard ring, with which the internal tab was supposed to engage. The test team turned the damaged drum upside down to demonstrate that the containment box could easily come out of the drum cavity by its own weight. A technician also noticed a crack in the corner welds of the shipping container insert, which was not visible prior to the test.

Figure 8. Damage to Open Drum, Side View

5.0 SUMMARY AND FINDINGS

In summary, the drop test accomplished its mission. Because the lid and closure device separated from the drum body in the 30-ft, 17.5º shallow-angle drop, the drop test confirmed that the common drum closure with a bolted ring is vulnerable to damage by a shallow-angle drop, even though the closure has been shown to survive much steeper-angle drops. The test program also demonstrated one of the mechanisms by which the shallow-angle drop opens the common bolted-ring drum closure.

The separation of the drum lid and closure device from the drum body was initiated by a large outward buckling deformation of the lid and completed with minimal assistance by the round plywood boards behind the lid. The energy spent to complete the separation appeared to be only a small fraction of the total impact energy. Limited to only one test, the present test program could not explore all possible mechanisms for the closure failure, some of which the test plan has described. The test program was also not intended to develop any quantitative design criteria for preventing drum closure failures. However, despite the limitation, the analyses of the test results offer valuable qualitative understandings of the shallow-angle impact. Following is a summary of the findings of this test program.

Drum closures, using the common bolted-ring closure system, can fail under shallow-angle drop conditions, even though such closure systems have been shown to be resistant to similar failures under steeper-angle drop conditions.

The shallow-angle drop can create failures of the common bolted-ring closure easier than the steep-angle drop, because, inherent in the impact direction and the closure design, the shallow-angle drop tends to drive the closure components apart, whereas the steep-angle drop tends to crush the components together. The puncture drop and the shallow-angle drop have similar ability, but the 40-inch puncture drop possesses much less damaging forces than that of the 30-ft shallow-angle drop.

The shallow-angle drop separates the lid and closure from the drum body by producing an outward buckling deformation of the drum lid, which is so large that the deformation of the drum body cannot match and the closure ring cannot restrain. The shallow-angle drop is also known to damage the drum closure by other means, such as breaking the lug welds of the closure ring.

The shallow-angle drop's ability to create a closure opening depends on the following factors: the drop orientation, the design detail and quality of the closure components, the package weight, and the integrity of the internal structure of the package. If the internal structure has no integrity, like liquid and powder, even the steep-angle drop can cause closure failures.

To ensure that standard bolted-ring drum closures can survive a shallow-angle drop, the following general qualitative rules should be observed:

- The drum-closure components should be quality products made of ductile materials.
- The package should not be too heavy.
- The package internal structure should be impact-absorbent and resistant to disintegration and collapse under high compressive loads. However, a strong internal structure may defeat the purpose of protecting the containment vessel from damage during a free drop.

To establish a quantitative relationship between the closure integrity and the affecting factors will require more than a few drop tests, even if the study is limited to only one specific package design. For this reason, the present single-drop test cannot offer general quantitative findings about shallow-angle drops of the test drum package. The present test only confirms that shallow-angle drops should be considered in the safety evaluation of drum packages that employ the bolted-ring closure system.

Since closure failures by the shallow-angle drop usually involve large deformations, geometric discontinuities, and structural instabilities, all of which are sensitive to design details and not amenable to regular mathematical analyses, the shallow-angle-drop evaluation of the drum closure should be conducted by test and on a case-by-case basis. Moreover, the familiarity with the package design and the understanding of the behavior of such packages under impact are essential for developing an adequate test plan.

The performance of the bolted-ring closure system depends on the torque value used to tighten the bolt. Therefore, the SAR of the package should contain the appropriate torque value.

By nature, the behavior of the bolted-ring closure under the shallow-angle impact can be rather unpredictable. This unpredictability may warrant a larger-than-usual margin of safety for this type of closure design. If the closure cannot be proven to remain closed under shallow-angle impacts, the possibility of the containment vessel being totally exposed should be considered in the evaluation of the package's capability to maintain the sub-criticality, containment, and shielding of the radioactive contents.

REFERENCES

1. Lewallen, E.E. 1972. "Drum and Board-Type Insulation Overpacks of Shipping Packages for Radioactive Materials," E.I. Dupont de Nemours & Co., Savannah River Laboratory, DP-1292, Aiken, SC, July.

2. Towell, Robert H. 1988. "Important Features Affecting Thermal Protection Provided by Drum and Fiberboard Packages," Proceedings of the 29th Annual Meeting of the Institute of Nuclear Materials Management, Vol. XVII, Las Vegas, Nevada.

3. Westinghouse Savannah River Corporation. 2001. "Safety Analysis Report — Packages, 9972–9975 Packages (U)," WSRC-SA-7, Revision 12, Radioactive Materials Packaging Technology, Savannah River Technology Center, Aiken, SC, June.

4. Hagler, L., M.K. Sheaffer, B.L. Anderson, R.S. Hafner, M.K. Witte. 2000. "Potential Vulnerability Issues for Drum-Type Packages," published in *Lisle Hagler, "Potential Vulnerability Issues for Drum-Type Packages," presented at the ASME PVP Conference, 2000. Proceedings of the ASME Pressure Vessel and Piping Conference*, PVP-Vol. 408, pp. 89-95, Seattle, Washington, July 23-27.

5. Hafner, R.S., G.C. Mok, L.B. Hagler. 2002. "Drop Test Results for the Combustion Engineering Model No. ABB-2901 Fuel Pellet Shipping Package," Lawrence Livermore National Laboratory, UCRL-ID-149067, June. See also, by the same authors, same title, NUREG/CR-6818, October 2003.

6. Combustion Engineering, Inc. 1997 "Application for Use of Model No. ABB-2901 Fuel Pellet Shipping Package," Certificate of Compliance No. 9274, NRC Docket No. 71-9274, April 8.

7. Title 10, Code of Federal Regulations, Part 71 (10 CFR 71), "Compatibility with the International Atomic Energy Agency (IAEA)," 60 FR 50248, September 28, 1995, as amended.

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